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Stress and field contactless sensor based on the scattering of electromagnetic waves by a single ferromagnetic microwire

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In this paper, we report an experimental study on the microwave modulated scattering intensity for a single $Fe_{2.25}Co_{72.75}Si_{10}B_{15}$ amorphous metallic microwire. The modulation is driven by applying a bias magnetic field that tunes the magnetic permeability of the ferromagnetic microwire. Furthermore, by using a magnetostrictive microwire, we also demonstrate that the microwave scattering is sensitive to mechanical stresses. In fact, we present a wireless microwave controlled stress sensor, suitable for biological applications, as a possible use of this effect. In addition, a first order theoretical approximation accounts for the observed influence of the magnetic permeability on the scattering coefficients. That model leads to predictions in good agreement with the experimental results. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4894732]

There is an increasing interest in understanding the interaction between ferromagnetic materials and microwave radiation.[1] Recently, many applications of microwave interacting ferromagnetic materials or metamaterials have been developed.[2] So far, the main uses of such materials are sensing applications[3] and microwave shielding systems.[4]

Amorphous ferromagnetic microwires are a type of magnetic material that has attracted much attention due to its unique magnetic properties.[5–7] Microwires are composed of a metallic inner core and a Pyrex outer shell both in the μm range. While the metallic core provides the magnetic behavior, the cover has a protective and stress-inducting function. Due to its tiny dimensions and its particular effects like Giant Magnetoimpedance (GMI),[8–14] bistability,[15] ferromagnetic resonance,[16] and magnetoelastic resonance, these materials have been considered as promising sensor elements. Furthermore, since the metallic core is covered by a biocompatible Pyrex shell, they are suitable for biological and medical applications. In this context, based on the GMI effect, it has been possible to develop a precise sensor element to detect the small magnetic fields associated with magnetic particles used as biomolecular labels.[17] In addition, a self-biased large magnetoelastic coupling factor has been obtained in microwires demonstrating its possibilities as contactless biosensor.[18,19] In this context, Co rich amorphous alloys with low magnetostriction have been found to exhibit outstanding GMI effect.[9]

There is much literature regarding microwave related applications of microwires or microwire- based materials.[20–24] Some of these articles have nicely shown how different arrangements of microwires forming arrays or embedded in different types of matrixes may be used for enhancing their sensitivity as GMI elements. In particular, the use of specific frequency dispersion of the wire arrays leads to outstanding GMI response.[21–23] However, experimental and theoretical studies of the effect of the magnetization on the scattering properties of a single microwire have not yet been deeply developed.

In this work, we present experimental evidence that the microwave scattering by a single microwire depends on the magnetic permeability with sufficient strength to be experimentally detected as an effect of the GMI. Furthermore, this dependence was also used to show the potential of such microwire as a wireless field and/or stress sensor. These experimental results are followed by a theoretical approach where the influence of the microwire magnetic state in its microwave reflection features is taken into account.

In order to show the magnetization influence of the microwire on it scattering properties, the following experiment was performed. A 10 cm length sample of $Fe_{2.25}Co_{72.75}Si_{10}B_{15}$ amorphous microwire of metallic core radius of $a = 33\,\mu$m and total radius, including the Pyrex outer shell, of $50\,\mu$m was placed between two helical antennas working in the GHz range with circular polarized radiation. We selected this composition because, as stated above, Co rich microwires are well known to exhibit a noticeable high GMI effect.[9] Due to its amorphous structure, even though they exhibit low or moderate magnetostriction are high sensitive magnetoelastic elements for detecting applied stresses as thoroughly discussed elsewhere since longtime ago.[25] Both antennas were connected to a two port AGILENT E8362B Network Analyzer. The microwire was arranged at 1.5 m of both antennas and orthogonal to the emission direction. The distance between antennas was large enough to ensure that a human body could be comfortably placed between them, and that the far field contribution dominates the near field one. In addition to that, an extra coil with a customized electronic set up was placed. This coil allows the application of a low frequency bias field parallel to the microwire axis. Figure 1 shows a sketch of our experimental set up and the geometry of the microwire.

Such experimental arrangement allows us to measure the scattering parameters of the system S_{ij}. The S_{ij} parameters are widely used in telecommunications engineering to describe radio frequency systems. They are defined as

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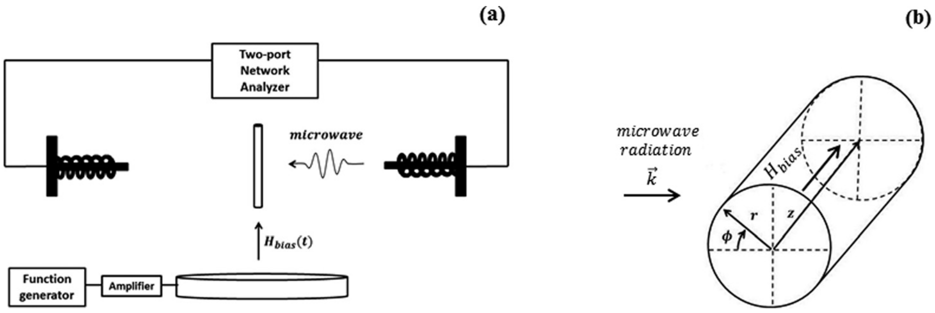

FIG. 1. (a) Experimental set-up. The microwire is placed equidistant between two GHz- helical antennas with the long axis perpendicular to the direction of propagation. Additionally a bias coil is placed in order to apply a low-frequency bias field along the microwire axis. (b) Geometrical arrangement of the microwire and the microwave and bias fields.

$$S_{ij} = 20\log_{10}\frac{P_i}{P_j} \quad ; i,j = 1,2, \tag{1}$$

where P_1 and P_2 stand for the power of the input and output signal, respectively. In our case, we restricted our study to the S_{21} parameter. The choice was based on its interesting physical meaning, since it represents the ratio between the measured power in the receiving antenna over the outgoing power in the emitting one.

Figure 2 displays the experimental result of measuring the S_{21} parameter over time for the aforementioned set-up with an emission frequency of the antennas set at $f_{antennas} = 1.2\,\text{GHz}$. The modulation of the S_{21} parameter shown in the Figure 2 is produced by the application of a bias field with frequency $f_{bias} = 100\,\text{mHz}$. Note that the modulated signal shows a frequency of $f_{mod} = 200\,\text{mHz}$, which is exactly twice the value of the bias frequency. This result suggests that the scattering is being somehow tuned by the magnetization of the sample, more precisely by its magnetic permeability μ_r. This doubled frequency is due to the symmetric shape of the microwire hysteresis loop ($|\mu_r(H_{bias})| = |\mu_r(-H_{bias})|$), as can be seen in Figure 3 in which the experimental hysteresis loop of the wire, measured using a quantum design vibrating sample magnetometer, as well as the low frequency permeability, that reaches values of 8×10^3, have been plotted.

Moreover, the use of even a weak magnetostrictive microwire, as the one chosen, allows us to modify its magnetic permeability by application of mechanical stresses. Figure 4 displays the result of an analogous experiment as the one depicted in Figure 1 but with the addition of a tensile device. Such device allows the application of different mechanical stresses to the microwire during the experiment. It can be noticed how the modulated pattern of S_{21} is modified under the application of the different mechanical stresses. In this case, the application of the stress induces a magnetoelastic anisotropy, with strength given by the product of the stress and the magnetization constant, that decreases the relative permeability, μ_r of the microwire.

The physical aspects underlying the experiments reported here are as follows. The modulation of S_{21} parameter observed in Figs. 2 and 4 describes the modulation of the reflected power P_2 at the receiving antenna position. The intensity of the wave reflected or scattered by the microwire shall depend on its impedance Z_2

$$Z_2 = \sqrt{\frac{i\omega\mu_0\mu_r}{\sigma}}, \tag{2}$$

where σ, ω, μ_0, and μ_r stand for the conductivity, frequency, vacuum permeability, and relative permeability, respectively. According to Eqs. (1) and (2), the bias field induces periodic changes of S_{21} as a consequence of the modulation that this field produces on μ_r as described by Figure 2. The periodic variation of μ_r gives rise through Eq. (2) to Z_2 and P_2 modulations that finally originates the experimental behavior summarized in Figs. 2 and 4. The figure of merit, β, we are interested in, is given by the following expression:

$$\beta = \frac{\Delta S_{21}}{S_{21}} = \alpha\Delta\mu_r, \tag{3}$$

where ΔS_{21} is the change of S_{21} originated by a change in permeability of strength $\Delta\mu_r$. Accordingly with previous considerations, the parameter α should be estimated through the dependence of both S_{21} on P_2 and from that of Z_2 on P_2.

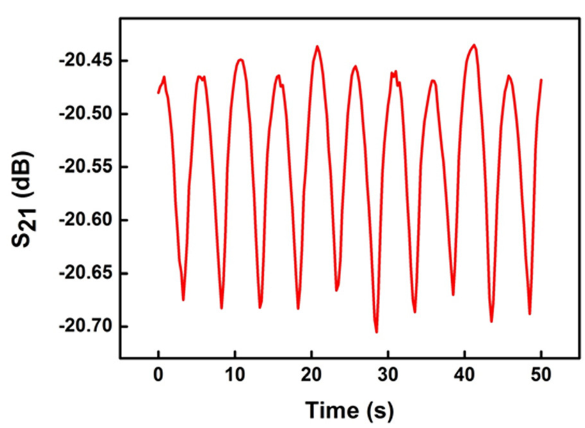

FIG. 2. Experimental S_{12} parameter time evolution for the experiment depicted in Figure 1 with $f_{antennas} = 1.2\,\text{GHz}$ and $f_{bias} = 100\text{mHz}$.

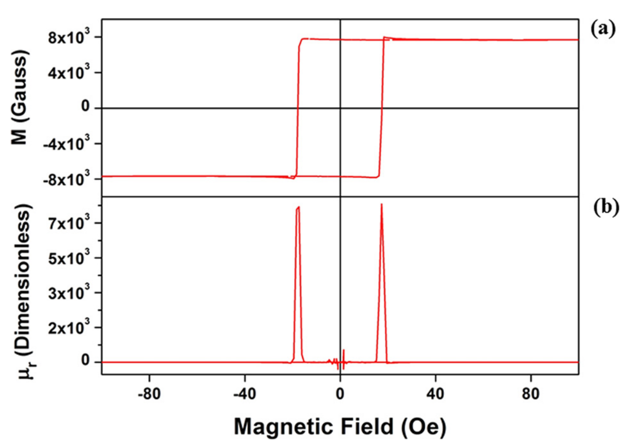

FIG. 3. (a) Hysteresis loop of the $Fe_{2.25}Co_{72.75}Si_{10}B_{15}$ sample. (b) Relative magnetic permeability of the $Fe_{2.25}Co_{72.75}Si_{10}B_{15}$ sample.

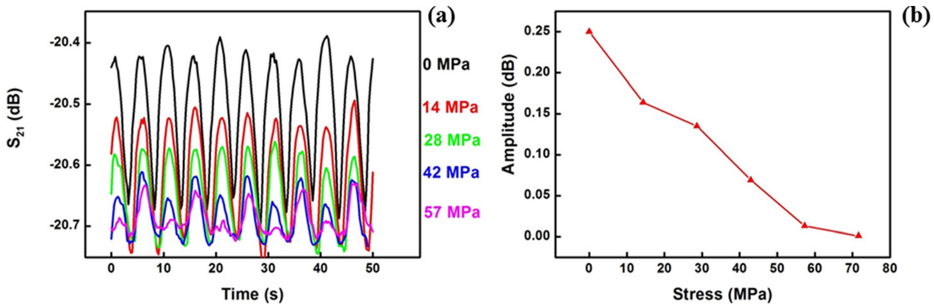

FIG. 4. (a) Experimental S_{21} parameter time evolution for the $Fe_{2.25}Co_{72.75}Si_{10}B_{15}$ microwire subjected to different mechanical stresses. (b) Peak to Peak amplitude of the S_{21} modulated signal as a function of the applied mass load.

The last one may be derived after using a standard method for calculating the scattering of electromagnetic waves by cylindrical ideal conductors, that can be found elsewhere in the bibliography.[26] Such procedure is strictly based on solving the boundary conditions of the incident and reflected fields at the inter-phase $r = a$, that in our case is the radius of the microwire metallic core. If we use the same geometry than in standard calculations[26] but considering a cylinder with finite conductivity and after expressing the magnetic, and electric fields as linear combinations of Bessel, I_i, and Hankel, H_i, functions, their boundary conditions yields, for the transversal Magnetic *(TM)* and transversal electric *(TE)* cases, the following reflection coefficients ($\widetilde{a}_i{}^{TE}$, $\widetilde{a}_i{}^{TM}$) of the Hankel, $H_i(k_1 r)$, functions describing the outgoing scattered wave

$$\widetilde{a}_i{}^{TE} = i^n \frac{Z_2 I_i(k_1 a) - Z_1 I_i'(k_1 a)\left(\dfrac{I_i(k_2 a)}{I_i'(k_2 a)}\right)}{Z_1 H_i^{(2)\prime}(k_1 a)\left(\dfrac{I_i(k_2 a)}{I_i'(k_2 a)}\right) - Z_2 H_i^{(2)}(k_1 a)}, \tag{4a}$$

$$\widetilde{a}_i{}^{TM} = i^n \frac{Z_1 I_{\mathrm{i}}(k_1 a) - Z_2 I_{\mathrm{i}}'(k_1 a)\left(\dfrac{I_i(k_2 a)}{I_i'(k_2 a)}\right)}{Z_2 H_{\mathrm{i}}^{(2)\prime}(k_1 a)\left(\dfrac{I_i(k_2 a)}{I_i'(k_2 a)}\right) - Z_1 H_i^{(2)}(k_1 a)}, \tag{4b}$$

where k_1, k_2 and Z_1, Z_2 stand for the wave vector and impedance in the air and in the material, respectively, and a is the radius of the microwire. It can be noticed that in the limit $Z_2 \to 0$ and $k_2 \to 0$, which correspond to a perfect conductor, Eqs. (4a) and (4b) are reduced to the well-known expressions for ideal cylindrical conductors.[26]

Contrary to the case of a perfect conductor, $\widetilde{a}_i{}^{TE}$ and $\widetilde{a}_i{}^{TM}$ are both function of Z_2 and k_2 which, in turn, are dependent on the magnetic permeability, see Eq. (2) and the following expression:

$$k_2 = \sqrt{i\omega\sigma\mu_{0r}\mu_r}. \tag{5}$$

Thus, it is possible to change $\widetilde{a}_i{}^{TE}$ and $\widetilde{a}_i{}^{TM}$ by tuning the magnetic state of the cylinder.

Some estimative considerations are outlined for a first order approximation that corresponds to the case in which only a_0 coefficients are relevant. In order to establish the correlation between the experimental parameter S_{21} and the theoretical scattering coefficients $\widetilde{a}_o{}^{TE}$ and $\widetilde{a}_o{}^{TM}$, we formulate the S_{21} parameter as a function of the scattering coefficients $\widetilde{a}_o{}^{TE}$ or $\widetilde{a}_o{}^{TM}$ by expressing the input and output power in Eq. (1) as the average value of the Poynting vector in the positions corresponding to both antennas. The explicit dependence of S_{21} with the theoretical scattering parameters is given by the following expression:

$$S_{21} = 20\log_{10}\left(\frac{(1 + \widetilde{a}_o{}^{circ}(\mu_{\mathrm{r}}))E_{in}^i(kr_2)}{E_{in}^i(kr_1)}\right)^2, \tag{6}$$

where E_{in}^i stands for the incident electric field, r_1 and r_2 represent the positions of the emitting and receiving antennas, respectively, and $\widetilde{a}_o{}^{circ}$ stands for the scattering parameter for circular polarized radiation. $\widetilde{a}_o{}^{circ}$ can be estimated as the mean value of the *TE* and *TM* modes. Figure 5 illustrates the S_{21} dependence on μ_r, as well as its derivative.

Carrying out a Taylor expansion of (6) and keeping only the linear terms, the value of β could be estimated from the results plotted in Figure 5 provided that the permeability is known. Note that the numerical value of the permeability from Figure 3 cannot be directly used for this estimation since it was measured at low frequency and for the GHz range the value of the magnetic permeability is always much smaller. However, Figure 2 clearly points out that regardless of its value for the high frequency range, the change of the permeability produced by the bias field must be big enough to generate an appreciable shift in the signal of the receiving antenna. Such change in permeability leads to a non-negligible sensitivity of the system with β reaching values of 10^{-3}, 10^{-2}, or even higher. This change might be further enhanced with suitable annealing of the microwire.[10,25]

It is also interesting to note that for driving field frequencies corresponding to magnetoelastic or ferromagnetic resonance frequencies of microwires, small variations of the applied field or stress can give rise to strong changes in permeability. In order to increase the sensitivity of the system, it is also important to select the frequency in that range for which the couple of antennas are close to resonance in wires. It must be noticed that we had outlined an estimation of the wire sensitivity without considering the tensor form of the permeability at the microwave range. A more rigorous analysis could be carried out, but to account for the order of magnitude of the experimental results reported in this letter the considered approximation seems to be sufficiently illustrative.

In summary, it has been experimentally shown that the microwave scattered intensity produced by a single microwire can be controlled by tuning its permeability. This permeability

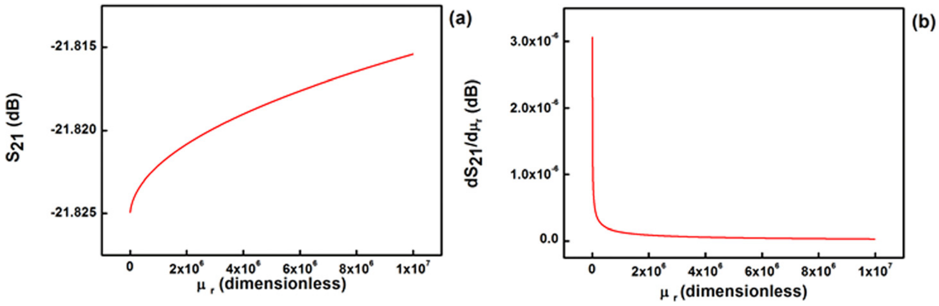

FIG. 5. (a) S_{21} dependence with the magnetic permeability. (b) $\frac{dS_{21}}{d\mu_r}$ dependence with the magnetic permeability. The curves were obtained from Eqs. (4a), (4b), and (6).

may be modified with the application of an external bias field, leading to non-negligible effects in the scattering. In addition, if the cylinder is magnetostrictive, the scattering is also sensitive to mechanical stresses. These experimental results are promising for future developments in this field including *in situ* and *in vivo* biomedical magnetoelastic experiments, taking advantage of the biocompatible nature of the microwire Pyrex cover. So far, these kinds of measurements were only possible by using GMI or Magnetoelastic Resonance based devices. However, the use of GHz frequency devices would allow the development of sensors operating at much longer distances and with a higher information transfer rate.

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[1]A. M. Hawkes, A. R. Katko, and S. A. Cummer, Appl. Phys. Lett. **103**, 163901 (2013).
[2]S. Yang, K. Lozano, A. Lomeli, H. D. Foltz, and R. Jones, Composites Part A **36**, 691 (2005).
[3]K. Vijayakumar, S. R. Wylie, J. D. Cullen, C. C. Wright, and A. I. Ai-Shamma'a, J. Phys. Conf. Ser. **178**, 012033 (2009).
[4]B. Yuan, L. Yu, L. Sheng, K. An, and X. Zhao, J. Phys. D: Appl. Phys. **45**, 235108 (2012).
[5]M. Vázquez and A. Hernando, J. Phys. D: Appl. Phys. **29**, 939 (1996).
[6]M. Knobel, M. L. Sanchez, C. Gomez-Polo, P. Marin, M. Vazquez, and A. Hernando, J. Appl. Phys. **79**, 1646 (1996).
[7]M. Vázquez, A. Zhukov, P. Aragoneses, J. Arcas, J. M. García-Beneytez, P. Marín, and A. Hernando, IEEE Trans. Magn. **34**, 724 (1998).
[8]H. Chiriac, M. Tibu, V. Dobrea, and I. Murgulescu, J. Optoelectron. Adv. Mater. **6**, 647 (2004).
[9]S. E. Lofland, S. M. Bhagat, M. Dominguez, J. M. Garcia-Beneytez, F. Guerrero, and M. Vazquez, J. Appl. Phys. **85**, 4442 (1999).
[10]S. I. Sandacci, D. P. Makhnovskiy, L. V. Panina, and V. Larin, IEEE Trans. Magn. **41**, 3553 (2005).
[11]S. I. Sandacci, D. P. Makhnovskiy, and L. V. Panina, J. Magn. Magn. Mater. **272**, 1855 (2004).
[12]L. V. Panina, S. I. Sandacci, and D. P. Makhnovskiy, J. Appl. Phys. **97**, 013701 (2005).
[13]M. Vázquez and D. X. Chen, IEEE Trans. Magn. **31**, 1229 (1995).
[14]D. X. Chen, J. L. Muñoz, A. Hernando, and M. Vázquez, Phys. Rev. B **57**(17), 10699 (1998).
[15]L. Kraus, G. Infante, Z. Frait, and M. Vázquez, Phys. Rev. B **83**, 174438 (2011).
[16]P. Marín, D. Cortina, and A. Hernando, J. Magn. Magn. Mater. **290**, 1597 (2005).
[17]G. V. Kurlyandskaya, M. L. Sánchez, B. Hernando, V. M. Prida, P. Gorria, and M. Tejedor, Appl. Phys. Lett. **82**, 3053 (2003).
[18]P. Marín, M. Marcos, and A. Hernando, Appl. Phys. Lett. **96**, 262512 (2010).
[19]C. Herrero-Gómez, P. Marín, and A. Hernando, Appl. Phys. Lett. **103**, 142414 (2013).
[20]H. X. Peng, D. X. Qin, M. H. Phan, J. Tang, L. V. Panina, M. Ipatov, V. Zhukova, A. Zhukov, and J. Gonzalez, J. Non-Cryst. Solids **355**, 1380 (2009).
[21]L. V. Panina, M. Ipatov, V. Zhukova, A. Zhukov, and J. Gonzalez, J. Appl. Phys. **109**, 053901 (2011).
[22]D. P. Makhnovskiy, L. V. Panina, C. García, A. Zhukov, and J. González, Phys. Rev. B **74**, 064205 (2006).
[23]Y. Luo, H. X. Peng, F. X. Qin, M. Ipatov, V. Zhukova, A. Zhukov, and J. Gonzalez, Appl. Phys. Lett. **103**, 251902 (2013).
[24]M. Flores, A. Calo, A. Gorriti, D. Cortina, G. Rubio, J. Grajal, and A. Hernando, J. Electromagn. Waves Appl. **28**, 202 (2014).
[25]A. Hernando, M. Vázquez, and J. M. Barandiarán, J. Phys E **21**(12), 1129 (1988).
[26]J. D. Jackson, *Classical Electrodynamics*, 3rd ed. (Wiley, New York, 1998).